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Visual summation of luminance lines and illusory contours induced by pictorial, motion, and disparity cues

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Abstract

Illusory contours where no contrast exists in the image can be seen between pairs of spatially separate but aligned inducing real contours defined either by pictorial cues (luminance contrasts or offset gratings), kinetic contrast, or binocular disparity contrast. In previous studies it has been shown that the detection of a thin luminous line is facilitated when the line is superimposed on illusory contours and the inducing flanking elements are defined by luminance contrast. By using a spatial forced-choice technique I show that luminous lines summate with illusory contours induced by luminance contrast, offset gratings, motion contrast, and disparity contrast when the line is superimposed on the illusory contour. Control experiments show that the positional cues, offered by the inducing contours, are unable to account for these results. It is suggested that real luminous lines or edges and illusory contours activate common neural mechanisms in the brain irrespectively of the stimulus attributes that induce the illusory contour.

Keywords: Illusory contours; Attribute-invariance; Summation; Neural-mechanism

1. Introduction

In natural viewing conditions it often happens that the outlines of objects and occluding contours are fragmentary since foreground and background may share the same surface characteristics, or due to dim lightning. In such situations the visual system estimates the location of object boundaries from the visible fragments of contours in the image leading to illusory contour formation. The ability to see illusory contours where no contrast exists in the image has received much attention since it was first discovered (Kanizsa, 1955; Schumann, 1900) and has been used as a tool to uncover neural mechanisms of visual gestalt laws (Davies & Driver, 1994; Dresp & Bonnet, 1991, 1993, 1995; Dresp & Grossberg, 1997; von der Heydt, Peterhans, & Baumgartner, 1984). These laws describe the visual systems remarkable ability to go beyond the information contained in the retinal images (Wertheimer, 1923). Although perceived contours may be mediated by contrasts in various information bearing media (such as luminance, texture, motion, and binocular disparity) research on illusory contours has almost exclusively focused on such contours completed between luminance defined inducing elements. An outstanding question that has not received much attention is whether mechanisms of perceptual grouping are attribute-specific or if cross-attribute grouping processes exist.

There is evidence that a substantial part of illusory contour formation is mediated by low-level mechanisms (Davies & Driver, 1994; Dresp & Grossberg, 1997; Dresp & Bonnet, 1993, 1995). Neurons in visual area V2 in the brain fire when a gap between collinear flanking elements is presented over their classical receptive field and the orientation preference of the neuron matches the orientation of the induced illusory contour (von der Heydt et al., 1984; Grosof, Shapley, & Hawken, 1993). Whether this activity reflects local processing in these areas or if it is mediated by top-down influences is still an open question. Computational modeling using known properties of neural interactions in computer simulations have shown that contour com-

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pletion processes may operate in low level visual areas (Grossberg & Mingolla, 1985; Heitger & von der Heydt, 1993; Li, 1998; Ross, Grossberg, & Mingolla, 2000).

Subthreshold summation techniques, originally used to measure summation between real contours (Kulikowski & King-Smith, 1977), have been introduced as a means of probing underlying illusory contour formation (Dresp & Bonnet, 1995). For example, the contrast detection threshold at which a thin target-line is detected is lowered when the target is superimposed on a subthreshold line aligned with the target-line (Kulikowski & King-Smith, 1977). These results have been interpreted in terms of a common neural mechanism activated by the target line and the subthreshold line. Activities triggered by either line would summate with activities triggered by the other and thereby lower detection threshold. The contrast detection threshold is also reduced when a non-oriented target is spatially superimposed on or near a low contrast luminance pedestal, but are raised at higher pedestal contrasts (Morgan & Dresp, 1995). Summation within a single receptive field may account for this result provided that the target and pedestal both fall within a single receptive field mediating target detection (Morgan & Dresp, 1995). Furthermore, detection thresholds for a small non-oriented target presented on an illusory contour is lower than if the target is presented adjacent to the illusory contour (Dresp & Bonnet, 1991, 1993). Likewise there is psychophysical evidence for near threshold summation between real and completed contours similar to the classical near threshold summation (Dresp & Bonnet, 1995). These findings have been interpreted as providing evidence in addition to the neurophysiological results for low level processing of contour completion since it seems that luminance induced illusory and real luminance contours share neural processing elements.

Research on visual contour completion has almost exclusively focused on luminance based inducers. However, perceptions of completed contours occur when other information-bearing media (attribute) than luminance is used to display the contours of the inducing elements. Spatially separate inducing contours defined by binocular disparity between randomly positioned texture elements give vivid perceptions of completed contours when the inducing contours are aligned (Julesz & Frisby, 1975; Mustillo & Fox, 1986; Poom, 2001). Similarly, spatially separate but aligned contours defined by relative motion between randomly positioned texture elements results in a perception of a completed contour, although neither real nor completed contours are seen without the motion (Kellman & Cohen, 1984; Poom, 2001; Prazdny, 1986).

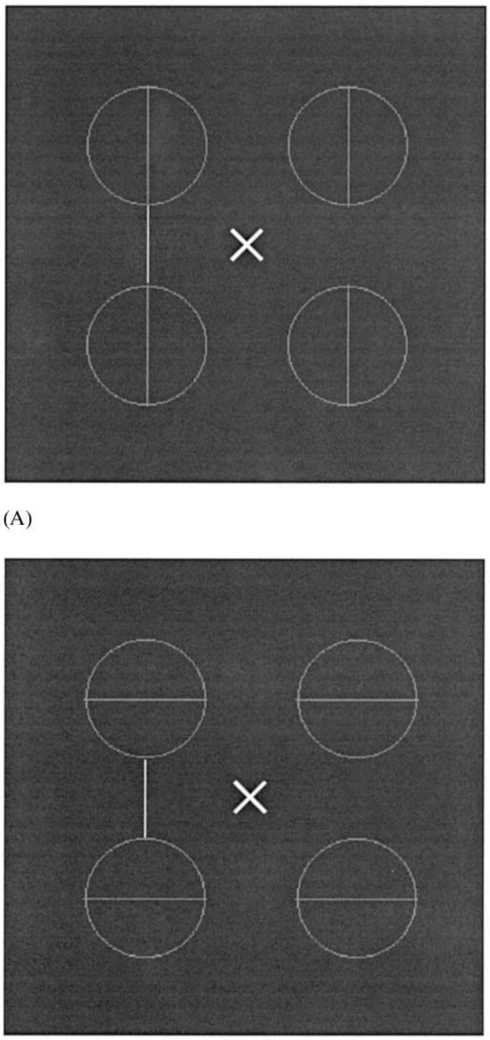
Poom (2001) used a subjective rating procedure to demonstrate that contour completion occur between pairs of inducers irrespectively if they are defined by the same stimulus attribute (intra-attribute conditions) or if they are defined by different stimulus attributes (inter-attribute conditions). This finding provides a demonstration of an attribute-invariant gestalt process, and may suggest that there exist a completion process that operates on attribute invariant contour detectors. In the present study I use an objective measurement technique with cross-attribute summation in an attempt to find out whether completed contours from various attributes summate with real luminance contrasts. This method provides a more rigorous test than provided by subjective rating procedures. Previous studies using the summation technique have shown that perceptually completed and real luminance defined contours have a common neural origin. Similarly, inter-attribute summation would provide evidence for the existence of a common neural representation of real luminance contours and illusory contours irrespectively of the stimulus attributes that induce them.

2. General methods

2.1. Apparatus and stimuli

The stimuli consisted of a thin vertical target line presented between pairs of inducing contours and was located either to the left or to the right of a fixation cross. A spatial forced-choice technique was used and the task was to indicate on which side the target-line appeared. Fig. 1 shows the experimental paradigm exemplified by one of the control stimuli used in Experiment 4 that was not supposed to induce any illusory contours. The contours were vertical and aligned with the target line (Fig. 1A), or horizontal and orthogonal to the target line (Fig. 1B). Luminance edges (Fig. 2A) and edges defined by offset gratings (Fig. 2B) were used as inducers in Experiment 1. Kinetically defined inducers were used in Experiment 2 (Fig. 2C), binocular disparity defined inducers in Experiment 3 (Fig. 3), and positional cues that did not elicit any perception of completed contours in Experiment 4 (an example of one such cue is shown in Fig. 1). Dresp and Bonnet (1995) used target lines that reached all the way to the boundary of the luminance defined inducers. A similar arrangement was used in Experiments 1–4. The ratio of the length of the physically specified contour to the total length of the contour, or support ratio (Shipley & Kellman, 1992), in Experiments 1–4 was 0.6 and the target line completely covered the illusory fraction of the contour. In Experiment 5 all the inducing elements used in the previous experiments were used again, the support ratio was decreased to 0.4 and the length of the target line was reduced to one fifth of the illusory fraction of the contour.

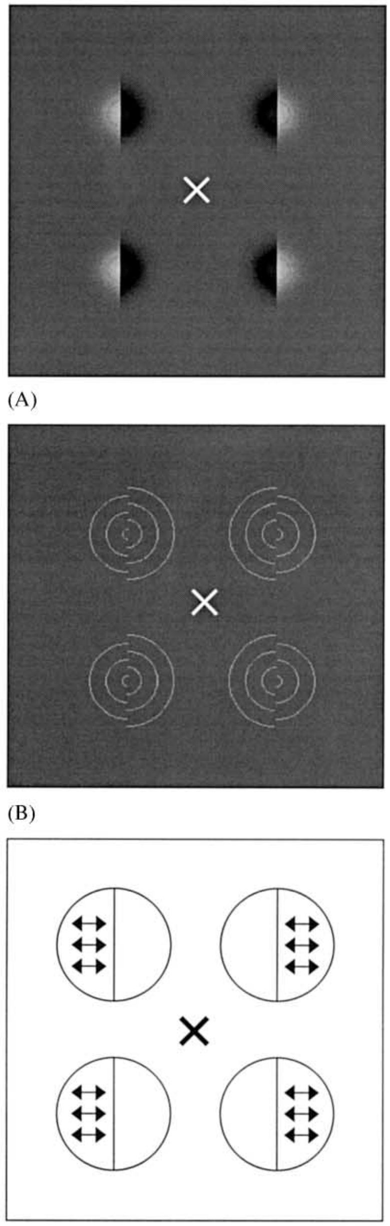
During free crossfusion of stereo pictures, or fusion through a polaroide filter stereoscope, the convergence of the eyes signal a closer distance than the accommodation. The resulting conflict due to the coupling between vergence eye movements and accomodation makes fusion difficult for some people during free fusion, or when using polaroid stereoscopes. It's possible to cancel this conflict by crossfusing stereo pictures viewed through a synopter, originally deviced to increase the perceived depth from pictorial depth cues in pictures (Koenderink, van Dorn, & Kappers, 1994). The synopter makes the point of view from the left and right eyes to coincide and the angle of convergence to be zero. The devise places the point of convergence-focus of the eyes at infinity although the point of accommodation focus is about the same as the actual distance to the picture. Therefore, cross-fusion of adjacent stereoimages through a synopter is facilitated since it makes the distance of convergence nearly coincide with the distance of accommodation. Thus the accommodation-convergence conflict, which is problematic during free fusion of stereoimages is avoided. Here I used a combination of a polaroid filter stereoscope and a synopter since it was found that fusion was effortless



(A)

(B)

Fig. 1. A luminous target-line is presented between pairs of inducing elements on either the left or the right side of the display under (A) aligned conditions, or (B) non-aligned conditions. The task was to indicate on which side the near threshold target-line was located. The inducing elements shown here typically do not give rise to perceptions of illusory contours. Such elements were therefore used as control stimuli in Experiment 4. In the actual experiments the fixation cross was not visible during target-line presentations.



(A)

(B)

(C)

Fig. 2. Contour completion occur between inducing elements that are defined by (A) luminance contrast, (B) offset gratings, or (C) kinetic contrast as displayed schematically. The arrows show the coordinated oscillation of texture elements in the motion defined contour inducer.

and unavoidable when the stereopairs were viewed through this devise.

Four inducing elements were simultaneously visible after fusion through the stereoscope. All inducers had a radius of 0.85° of visual angle. In half the experimental sessions all the inducing contours were vertically aligned resulting in perceptions of completed contours aligned with the target-line. In the other half of the experimental sessions they were horizontally oriented and the completed contours were orthogonal to the target-line as demonstrated in Fig. 1. The only contextual difference between these conditions is the orientation of the real and illusory contours. The target line had a width of one pixel throughout the experiments and it was aligned with the inner edges of the inducing elements when it was superimposed on the illusory contour. The luminance contrast between the target-line and background was varied between sessions. The background had a fixed luminance throughout the experiments (0.37 cd/m^2). All inducing elements were made clearly visible against the background to produce perceptions of illusory contours. Both the orientation of the inducing contours and the luminance levels of the target-line was fixed within sessions.

A computer program was developed and run on a PC compatible hardware to create the stimuli and collect the data. The patterns were displayed on a 17-inch (1024 $\times$ 768) screen with 75 Hz refresh rate and 32-bit color depth (true color). The viewing distance was 100 cm.

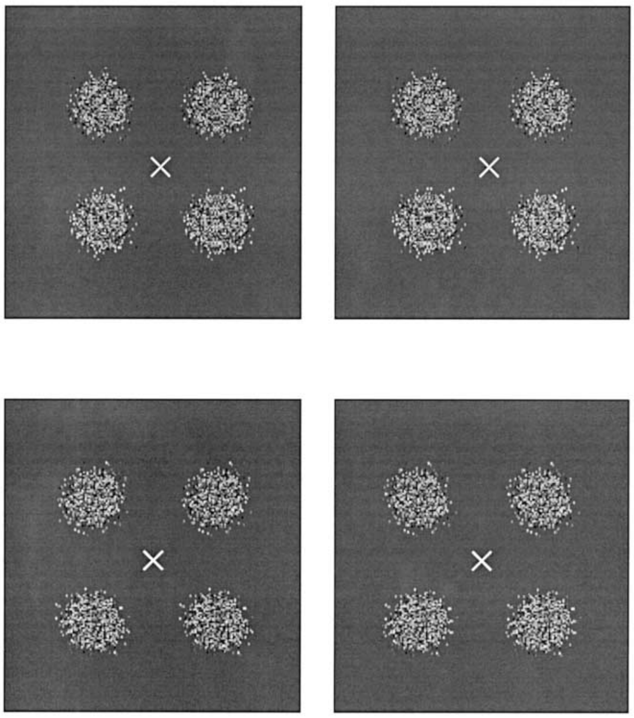


Fig. 3. Crossfusion of the stereo pictures reveal an illusory contour completed between the edges of the inducers although no signals are available between them. Vertical contours in the top panels, and horizontal contours in the bottom panels.

2.2. Subjects

The same three observers participated in the first four experiments, the author (L.P.) and two female undergraduate psychology students (M.N. and J.B.) naive to the purpose of the experiment although relatively experienced as observers. Six other undergraduate psychology students participated in Experiment 5. All participants had normal visual acuity and were tested for the ability to see depth in random dot stereograms viewed through the stereoscope. They all reported that the disparity defined edge and the depth order was effortlessly perceived. Before the experiments started each observer went through training trials to get used to the procedure.

2.3. Procedure

Observers were presented pairs of sessions with 100 trials each. After each session the orientation of the inducers was changed and the next session in the pair was performed. The orientation of the four inducers was either vertical or horizontal in the first session and the opposite orientation in the second session. After each pair of sessions was competed a new setting of the luminance level of the target-line was randomly chosen together with the orientation of the inducing elements. Pairs of sessions were presented in random order. Blocks of sessions with the same stimulus attributes defining the inducing elements were performed successively. Each block was completed in the same experimental occasion but some of the blocks were performed at consecutive days in order to avoid fatigue of the observers.

A spatial forced choice technique and the method of constant stimuli was used in all the experiments. The observer's task was to indicate on which side the luminous thin target-line was located. Observers indicated their responses by pressing the left or right arrow keys on the computer keyboard. The inducing elements were displayed continuously during each experimental session. The target line was visible for 350 ms for subject L.P. and 750 ms for the other two subjects. The longer presentation time was used for subjects M.N. and J.B. since it was found in preliminary investigations that they could not do the task at 350 ms, probably since L.P. was highly experienced in this task compared to the other two subjects. The target line appeared on the screen 200 ms after the spacebar was pressed. A red fixation cross was visible in the middle of the display, it vanished during target-line presentations and reappeared immediately after the target-line disappeared.

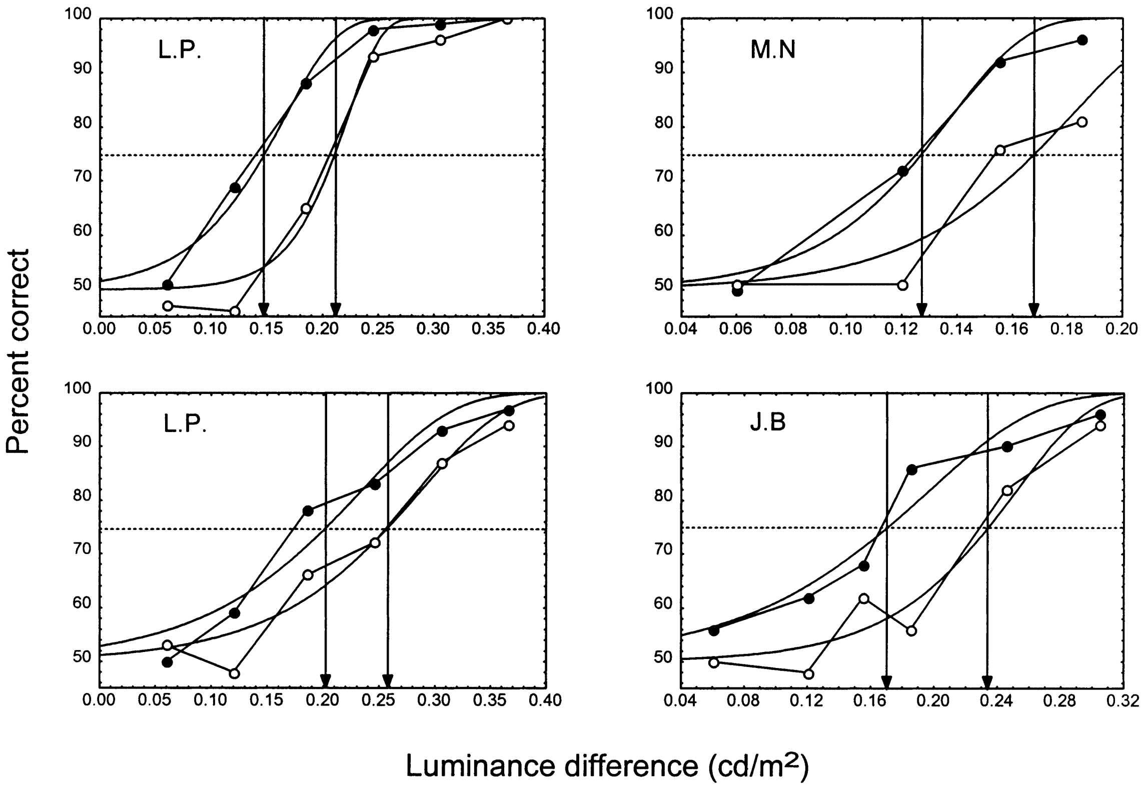


Fig. 4. Results of Experiment 1 with summation of illusory contours from pictorial cues and luminance lines. The percentages of correct responses are shown (as a function of the luminance difference between the target-line and the background luminance) for three observers and the corresponding fitted psychometric functions. Observer L.P. was tested for both the luminance defined inducing elements (top left) and offset concentric gratings as inducing elements (bottom left). Observers M.N. and J.B. were tested with the offset gratings only. Open circles show the performance with inducing contours orthogonal to the target-line. Filled circles show the percent correct when the target-line was superimposed and aligned with the illusory contour. The arrows show the locations for the 75% thresholds as indicated by the intersection between the horizontal dotted line and the psychometric functions.

The proportion of correct responses was displayed on the screen after each session of 100 trials was completed. Feedback was given during sessions in the form a soft 'beep' when a wrong response was made.

3. Experiment 1

Dresp and Bonnet (1995) showed that near threshold lines of either contrast polarity summate with illusory contours completed between luminance defined inducers of either sign. This finding has been taken as evidence that real luminance contours and contours perceptually completed between luminance defined inducing elements activates common neural mechanisms (Dresp & Bonnet, 1995; Dresp & Grossberg, 1997). Furthermore the results show that the genesis of illusory contours involve mechanisms that are insensitive to the sign of contrast. It has been suggested that illusory contours induced by line-ends and those induced by luminance contrasts are mediated by different mechanisms (Halpern, 1981; Petry, Harbeck, Conway, & Levey, 1983). The summation technique may provide further insights in this question.

3.1. Stimuli

The four inducers were centered the corners of a square with side length 2.8° of visual angle. The inducers were defined by polarity contrasts across gaussian luminance blobs on gray background as shown in Fig. 2A, or concentric, white off-set gratings where the inducing contour itself is illusory as shown in Fig. 2B. Polarity contrasts across luminance blobs has been shown to elicit much stronger perceptions of illusory contours than the traditionally used Kanizsa packman figures (Poom, 2001). The separation between pairs of inducers as well as the length of the target-line was 1.1° and the support ratio of the illusory contour was 0.6.

3.2. Results

The results are shown in Fig. 4. A Weibull psychometric function was fit to the data. The threshold was defined as 75% correct responses and is shown by the horizontal dotted line. The arrows show the estimated locations of the thresholds, in terms of the luminance difference between the target and the background, as estimated by the psychometric functions. As expected, the threshold for detecting the vertical luminous target line decreases when the target is superimposed on the illusory contour compared to the situation where the inducers are horizontally oriented and thus not aligned with the target (from 0.21 to 0.15 cd/m^2, Fig. 4, subject L.P. top left panel). This result is similar to the findings by Dresp and Bonnet (1995). Similar results are obtained when offset circular gratings are used as inducing elements (Fig. 4 down leftmost panel and both rightmost panels). The threshold was reduced from about 0.26 to 0.20 cd/m^2 for L.P., from 0.17 to 0.13 cd/m^2 for M.N., and from 0.23 to 0.17 cd/m^2 for J.B. Only observer L.P. participated in sessions with the luminance blobs as inducing elements since this was considered to be a replication of previous studies (Dresp & Bonnet, 1995).

Contrast detection is facilitated if a near threshold target is presented nearby a low contrast luminance pedestal, and reduced for higher pedestal contrasts (Morgan & Dresp, 1995). However, the present results cannot be accounted for by any contextual brightness differences since the brightness of the flanking inducers are the same in both orientation conditions. This indicates that illusory contours and luminous lines share a common representation irrespectively whether the contour is completed between inducers defined by luminance contrast or offset gratings.

4. Experiment 2

Relative retinal motion is a powerful source of information to reveal distal figure-ground relationships and structure. Spatially separate but aligned contours defined by motion induce strong perceptions of illusory contours (Kellman & Cohen, 1984; Poom, 2001; Prazdny, 1986). Although motion, luminance, and texture contrasts are intra-ocular cues they require qualitatively different mechanisms. Signals from intra-ocular spatial positions are compared when figure-ground segmentation and structure is estimated from pictorial cues, but retinal signals have to be compared over time to estimate structure-from-motion and figure-ground from motion. Although the pictorial and motion attributes require different mechanisms, they produce equally strong illusory contours, as shown in rating experiments (Poom, 2001), when completion between any pair combination of such attributes is to be achieved. The near threshold summation technique is used here to investigate the possible effect of summation between motion induced illusory contours and luminance-defined lines. Such summation would be expected if both these types of contours have a common neural representation.

4.1. Stimuli and procedure

Motion contrast between randomly gaussian distributed and randomly colored texture elements were used as inducing contours. Each cloud of dots gave colored confetti like appearance. One frame of the motion sequence appeared like one picture of the stereopairs in Fig. 3. No inducing contours, and hence no completed contours, could be seen in single frames from the motion sequence. This resulted in a perception of an edge of a stationary surface occluding another moving surface oscillating behind the occluder. The moving dots disappeared when they passed the midline of the inducer, and reappeared when the motion direction shifted (Fig. 2C). The orientation of the contour was vertical and aligned with the target-line, or horizontal and orthogonal to the target-line. The moving dots oscillated back and forth with 0.17° of visual angle amplitude and with a frequency of 2 Hz. The motion was always orthogonal to the contour, horizontal when the contour was vertically oriented and vertical when the contour was horizontally oriented. Other stimulus parameters were the same as in Experiment 1.

4.2. Results

When the luminous target-line is superimposed on the illusory contour completed between the kinetically defined inducers, the detection of the target-line is facilitated compared to when the contour is orthogonal to the target-line (Fig. 5). The estimated 75% correct thresholds were reduced from about 0.23 to 0.20 cd/m^2 for L.P., from 0.20 to 0.15 cd/m^2 for M.N., and from 0.23 to 0.15 cd/m^2 for J.B., as indicated by the arrows. Thus, the luminous target-line summates with completed contours defined by kinetically inducing elements. A parsimonious explanation of the results is that completed contours from kinetically defined inducing elements and luminance-defined contours share a common neural representation in the brain.

5. Experiment 3

Experiments 1 and 2 show that luminous lines summate with pictorially and temporally induced completed contours. Pictorial and temporal attributes are both defined intra-ocularly. A third information bearing media is binocular disparity, which by definition is an inter-ocular attribute. Vivid perceptions of structure and figure-ground relationships can be formed with random dot stereograms devoid of other information than disparity between the corresponding texture elements (Julesz, 1964). Also, perceptions of illusory contours may be generated by disparity defined inducers (Julesz & Frisby, 1975; Mustillo & Fox, 1986; Poom, 2001). Here I attempt to investigate whether illusory contours from disparity defined inducing elements summate with superimposed aligned luminance lines. Summation is expected if disparity-defined illusory contours and real luminance lines activate the same neural substrate.

5.1. Stimuli

The inducing elements defined by binocular disparity were created with the same texture arrangement as the kinetic inducers (Fig. 3). The display was static and the contour was made visible by a horizontal shift (7 arcmin) of the dots belonging to the 'far' surface between the right and left image so that an edge of a near surface appeared in front of a far surface (Fig. 3). The appearance was a contour of a near surface, cutting the dot cloud in half, and a far surface on the other side of the contour. The depth plane of the near surface was the same as the depth position of the target-line. In half the experimental sessions the disparity contours were aligned with the vertical target-line and in the other half they were horizontally oriented and orthogonal to the target-line. Other stimulus parameters were the same as in Experiment 1.

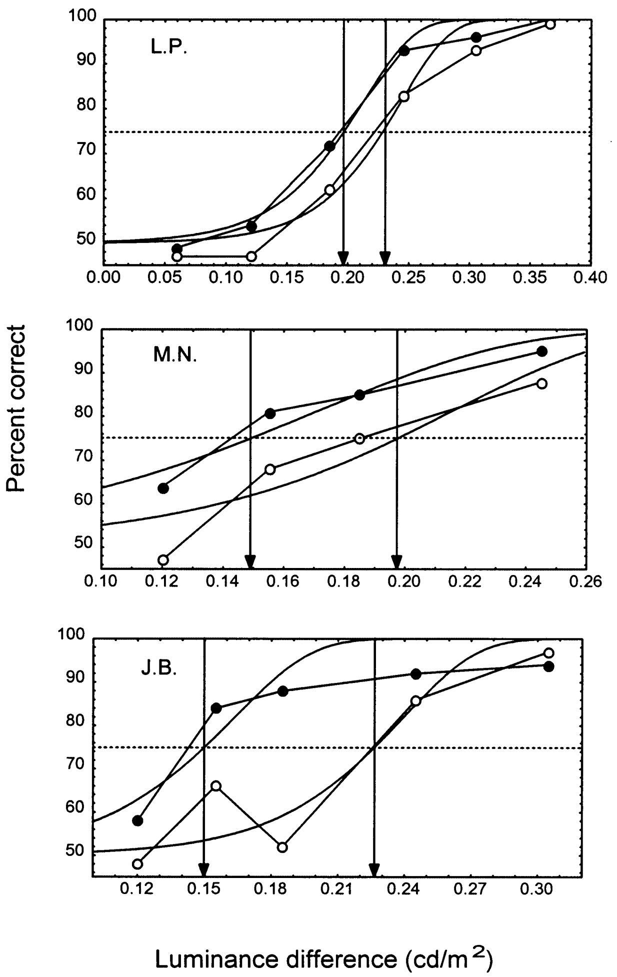


Fig. 5. Results of Experiment 2 with summation of illusory contours from motion cues and luminance lines. The percentages of correct responses are shown (as a function of the luminance difference between the target-line and the background luminance) for three observers and the corresponding psychometric functions. The inducing contours were defined by motion contrasts. Open circles show the performance when inducing kinetic contours orthogonal to the target-line were used. Filled circles show the percentage correct when the target was superimposed and aligned with the illusory contour. The arrows show the locations of the 75% thresholds.

5.2. Results

The result shows that when the binocular disparity defined inducing contours are used, and their orientations are aligned with the luminous target-line, then performance is better than if the inducers are orthogonal to the target-line (Fig. 6). The estimated 75% correct thresholds were reduced from about 0.23 to 0.17 cd/m^2 for L.P., from 0.19 to 0.14 cd/m^2 for M.N., and from 0.23 to 0.20 cd/m^2 for J.B., as indicated by the arrows. Summation occurs between luminous thin lines and contours completed between inducing contours defined by binocular disparity, which is an inter-ocular cue. This indicates that the summation occurs on a stage subsequent to monocularly driven neural processing.

6. Experiment 4

One possible explanation for the results from Experiments 1–3 is that the aligned inducing contours offer positional cues to the location of the target-line and therefore improve performance compared to when the inducing contours are horizontally oriented. Although the inducing blobs offer positional cues irrespectively of the orientation of the contour, the precision increases when the contours are aligned with the target-line. The aim of Experiment 4 is to investigate to what degree the positional cues might have caused the results in the prior experiments by using positional cues that does not give rise to perceptions of illusory contours.

6.1. Stimuli

The positional cues, not supposed to induce illusory contours, were created by thin outline luminous concentric circles (diameter 1.7°) with a line that could be oriented either vertically (Fig. 1A) or horizontally across the circle (Fig. 1B). Another positional cue was displayed by outlined arrowheads created by line segments pointing to the ends of the target line (not shown). A similar positional control stimulus was used in the Dresp and Bonnet (1995) study. The location of the positional cues was the same as the inducers in

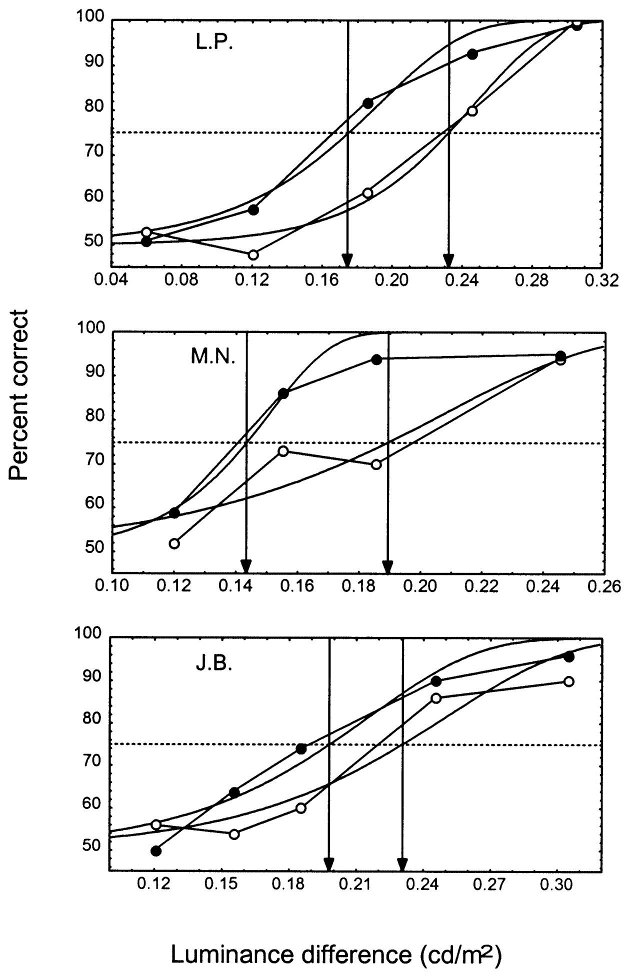


Fig. 6. Results of Experiment 3 with summation of illusory contours from disparity cues and luminance lines. The percentages of correct responses are shown (as a function of the luminance difference between the target-line and the background luminance) and the corresponding psychometric functions for three observers. The inducing contours were defined by binocular disparity contrasts. Open circles show the performance with inducing disparity-defined contours orthogonal to the target. Filled circles show the percentage correct when the target-line was superimposed and aligned with the illusory contour. The arrows show the 75% thresholds.

Experiment 1, also the length of the target line was the same.

6.2. Results

Observers M.N. and J.B. were unable to take advantage of the positional cue offered by the vertical line segments aligned with the target-line compared to when the line segments were horizontal (Fig. 7). The estimated locations of the 75% threshold were nearly coincident at about 0.16 cd/m^2 in both conditions for subject M.N., and increased from 0.21 in the vertical condition to 0.22 cd/m^2 in the horizontal condition for J.B., as indicated by the arrows. For one subject (L.P.) it seems that the positional cue offered by the outline circles having vertical lines aligned with the target-line aid detection compared to when it's is not aligned with the target-line (the thershold decreased from 0.20 to 0.17 cd/m^2). However, this positional cue was occasionally perceived as a partially occluded amodally completed line partly visible through circular holes and extending behind the occluder. Therefore, observer L.P. used an additional positional cue consisting of arrowheads. This positional cue did not elicit either modally or amodally completed contours. The arrowheads did not improve performance compared to the outline circles, the threshold decreased from 0.20 cd/m^2 with the circles to 0.19 cd/m^2 with the arrowheads. It can be concluded that the positional cues are unable to im-

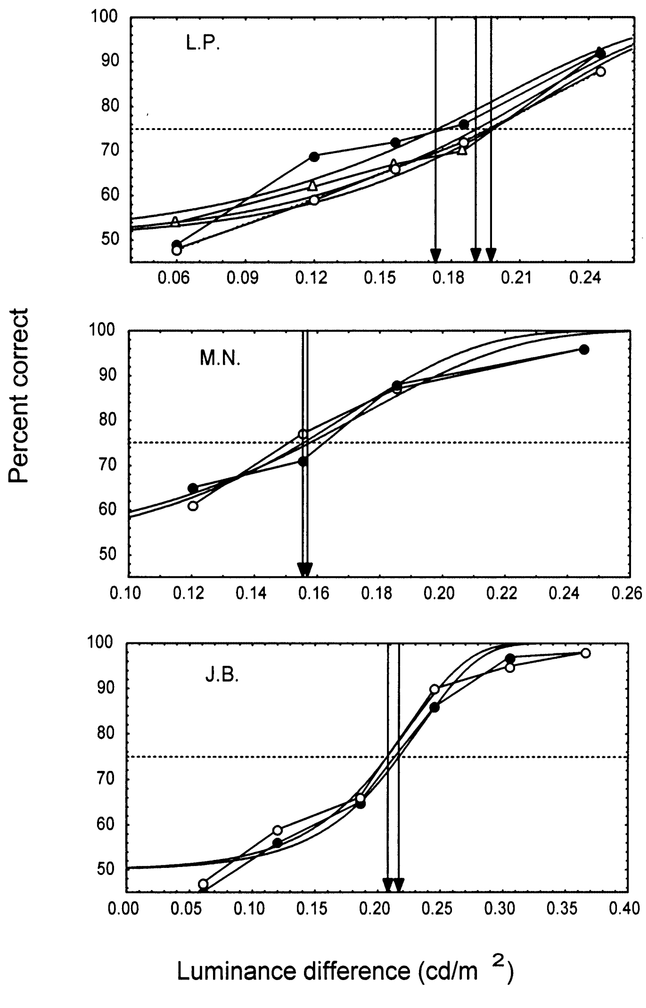


Fig. 7. Results of Experiment 4 with positional cues to the luminance lines. The percentages of correct responses are shown (as a function of the luminance difference between the target-line and the background luminance) for three observers and the corresponding psychometric functions. Positional cues were used to indicate the exact location of the target. Open circles show the performance when lines within the outline circles are orthogonal to the target. Filled circles show the percentage of correct responses when the lines within the outline circles are orthogonal to the target. Observer L.P. was tested with an additional positional cue composed of arrowheads (results shown by open triangles). The arrows show the 75% thresholds.

prove performance. Although it's beyond the scope of this work the result from subject L.P. may indicate that amodally-completed lines activate the same neural mechanisms as do real luminance lines. After the observers M.N. and J.B. had completed their experimental sessions they were asked if they had perceived the display as an amodally occluded line, but neither of them had. Since no difference could be seen from their results, between the two orientations of the lines within the flanking circles, it was concluded that it was unnecessary to continue the experiment using the arrowheads as positional cues. Thus, the results from Experiments 1–3 cannot be accounted for by the positional cues offered by the contours of the inducing elements when they are aligned with the target-line.

7. Experiment 5

In the previous experiments the target line reached all the way to the boundary of the inducers as did the target line in the study of Dresp and Bonnet (1995). As a consequence the measured effects on threshold could have been due to local summation within regions immediately adjacent to the inducer boundaries. In Experiment 5 the target line was shortened and the distance between the inducing elements was lengthened.

7.1. Stimuli and procedure

The same inducing elements that were used in Experiments 1–4 were also used in Experiment 5. The arrowheads and outlined circles used as a control condition in Experiment 4 were used for the same purpose in Experiment 5. The vertical separation between the inducers was increased from 1.1° in the previous experiments to 2.5° in Experiment 5 giving a support ratio of 0.4, and the target line length was decreased from 1.1° to 0.5°. Thus, the separation between the target line and the boundary of the inducers was 1° of visual angle.

All participants went through training sets before each experimental condition. In all stimulus conditions the participants went through pairs of 60 trials each in aligned and unaligned inducer orientations, respectively. Since fine coarse stereopsis required for seeing the disparity defined edges is limited to foveal regions and the inducing elements now appeared far apart the presentation time was increased to 1000 ms to allow scanning of the display. In preliminary investigations it was found that vivid perception of disparity edges and the accompanying illusory contours required such scanning. In all other respects the experimental procedure was the same as in the previous experiments.

7.2. Subjects

Six undergraduate students participated as observers in all conditions in Experiment 5. They were all naive as to the purpose of this study.

7.3. Results

The data were collapsed across all six observers for each stimulus condition. The results shown in Fig. 8 reveal that the threshold for detecting the target line is reduced only when the line is superimposed on the illusory contour irrespectively of the attributes used as inducers. The 75% correct thresholds were reduced from about 0.22 to 0.17 cd/m^2 for the motion inducers; from 0.21 to 0.17 cd/m^2 for grating inducers; and from 0.23 to 0.20 cd/m^2 for the disparity inducers (indicated by the arrows). No such large threshold reduction occurred when the arrowheads, not inducing any illusory contours, were used to indicate the position of the target. The data points almost overlap and the estimated 75% thresholds are 0.22 cd/m^2 with circles and 0.21 cd/m^2 with the arrow heads. Since there is a gap of 1° between the inducers and the target line in Experiment 5, the threshold reduction obtained in Experiments 1–3 or in the study of Dresp and Bonnet (1995) cannot be accounted for by a strict local effect near the inducer boundaries.

8. Discussion

By using a subjective rating procedure it has been shown previously that clarity ratings of inter-attribute completed contours are as high as the corresponding intra-attribute ratings (Poom, 2001). Others have shown that near threshold luminous target-lines summate with illusory contours completed between luminance-defined inducers and concluded that perception of real and illusory contours result from a common mechanism (Dresp & Bonnet, 1995). The results presented here show that luminous lines perceptually summate with completed contours irrespectively of what stimulus attributes define the inducing contours. The results cannot be accounted for by positional cues at the inducer boundaries since such cues in configurations without illusory contours failed to improve performance as shown by the results from Experiment 4 and the control condition in Experiment 5. There is a possibility that inhibition between orthogonally oriented edges detectors may have increased threshold when the inducing contours were horizontally oriented and orthogonal to the target line. Inspection of Fig. 8 show that the thresholds were the same in the control conditions (0.21 and 0.22 cd/m^2 for the arrowheads and the circles, respec-

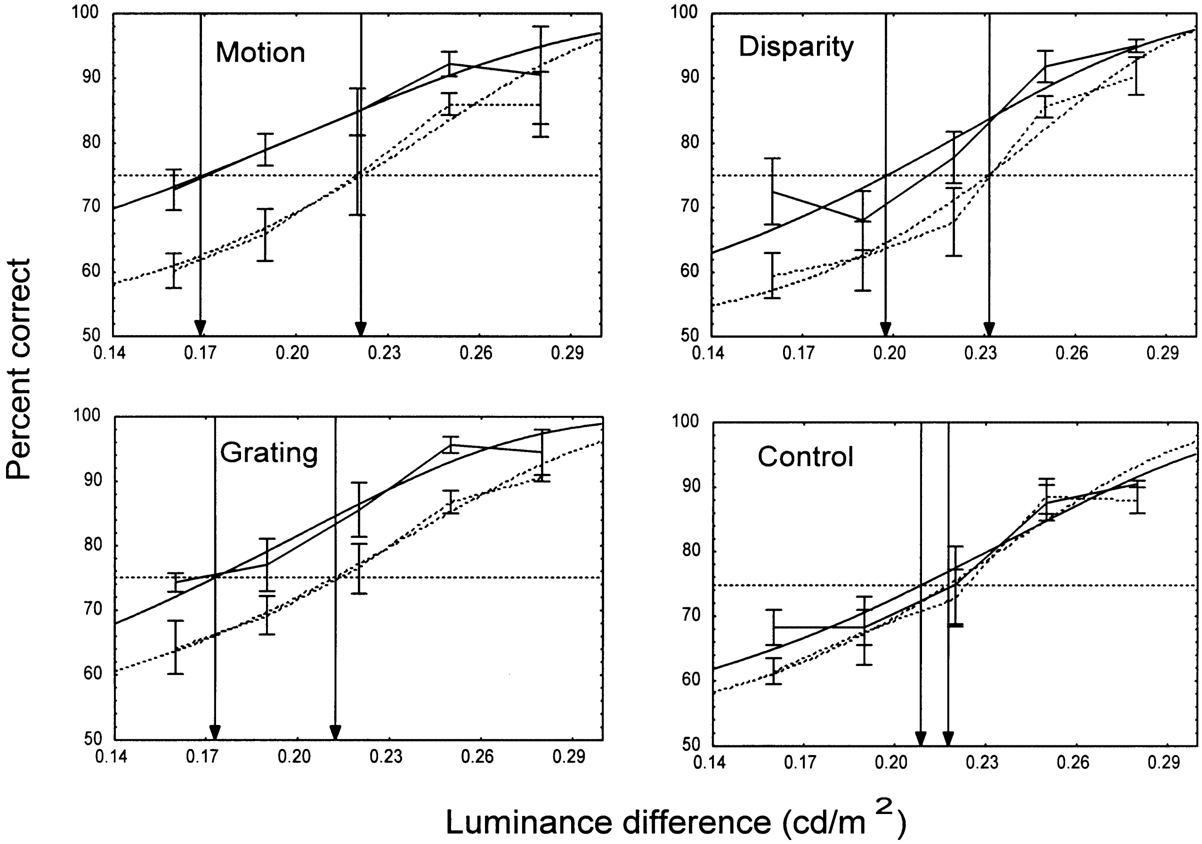


Fig. 8. Results of Experiment 5 with the target and the inducers separated by 1°. The mean percentages of correct responses are shown across six observers (as a function of the luminance difference between the target line and the background luminance) and the corresponding psychometric functions. The different inducer conditions (offset concentric gratings, motion, disparity, and arrowheads as positional control cues) are presented separately in the four panels. The continuous lines show the results when the target is superimposed on the illusory contour and the positional cue in the control condition. The dotted lines show the results for horizontally oriented inducers and the circles in the control condition. The bars show ± 1 S.E. and the arrows show the 75% thresholds.

tively) as when horizontally oriented inducing elements were used (ranging from 0.21 to 0.23 cd/m^2), which argues against any inhibition. The threshold reduction is not due to summation within the regions near the boundary of the inducers since the same result is obtained when the target line is spatially separate from the inducers as shown by the results from Experiment 5. The results might be accounted for by the mathematical operation of probability summation; independent filters detect the luminance line and the illusory contour, and a max operator makes the decision. However, the neural implementation of probability summation requires that signals from different independent channels converge at some point (Tyler & Chen, 1999). Attribute-invariant contour detectors with receptive fields large enough to include both the inducing contour and the target line may also account for the results. Another explanation of the present results is that an attribute-invariant contour-completion process operates in the visual system. Field, Hayes, and Hess (1993) used the general term 'association field' without relating it to specific neural processes to describe the spatial constraints of illusory contour formation. Inter-attribute contour completion may be accomplished by attribute invariant input to such association fields (Poom, 2001). The properties of such association fields have a physical basis in the statistics of edge co-occurrences in natural images (Geisler, Perry, Super, & Gallogly, 2001).

Various neural models have used bipole filters (Grossberg & Mingolla, 1985) or other long-range completion processes (Finkel & Edelman, 1989; Heitger & von der Heydt, 1993; Peterhans, von der Heydt, & Baumgartner, 1986). It has been pointed out that bipole filters can describe all these long-range completion processes by appropriate tuning of the receptive lobes (Lesher, 1995). Neurophysiological measurements have shown that such couplings between neurons do exist (for a review see Callaway, 1998). Especially, neural facilitation in primary visual cortex occurs when a near threshold target stimulus, inside the classical receptive field, is flanked by collinear elements in the surrounding regions of visual space outside the receptive field (Polat, Mizobe, Pettet, Kasamatzu, & Norcia, 1998). Kapadia, Ito, Gilbert, and Westheimer (1995) measured contrast sensitivity of oriented target-lines for human observers and found that the sensitivity improved 40% by presenting a second flanking high contrast line. The effect was reduced when the distance increased along their axis of orientation, or they were displaced from collinearity, or if their relative orientation changed, or if an orthogonal line was presented between the iso-oriented lines. By using the same stimulus settings they also made recordings of neural responses from complex cells in area V1 in alert monkeys. These cells responded with a similar dependency on location and relative orientations, as did the human observers. These studies may reveal the neural basis for the psychophysical observations on humans of visual spatial interactions and grouping processes.

Kinetic contours and luminance contours seem to be processed by common neural mechanisms in cortical area V2 (Marcar, Raiguel, Xiao, Maes, & Orban, 1992), and so do texture and luminance defined contours (Mareschal & Baker, 1998), as well as disparity and luminance defined contours (von der Heydt, Zhou, & Friedman, 2000). The existence of attribute invariant contour detectors in early visual areas has been supported by psychophysical studies using the tilt illusion as a tool. Double dissociation of tilt attraction and repulsion effects between luminance gratings has been interpreted as the repulsion effect arise in low level cortical areas such as V1 and/or V2, and the attraction effect is believed to arise in areas beyond V2 (Wenderoth & Johnstone, 1987, 1988). Both the repulsion and attraction effects, and the double dissociation, are attribute invariant (Poom, 2000). They occur even when the inducing grating and the test grating are defined by different stimulus attributes such as luminance, motion, and disparity defined gratings. This result provide psychophysical evidence for attribute-invariant contour detection mechanisms in cortical areas V1 and/or V2.

In conclusion, both neurophysiological and psychophysical results provide evidence for the existence of attribute-invariant contour detectors in cortical areas V1 and V2. Also, there exists psychophysical evidence for low level contour completion mechanisms operating on luminance defined inducers (Dresp & Bonnet, 1993, 1995) and neurophysiological evidence for the existence of such processes in visual areas V1 and V2 (Grosof et al., 1993; von der Heydt et al., 1984). These findings together with the results presented here indicate that so-called association fields in contour completion (Field et al., 1993) may be operating on attribute-invariant input.

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